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ON THE EFFECT OF SURFACE EMISSIVITY ON TEMPERATURE RETRIEVALS

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ABSTRACT

The variability of surface emissivity over land, and the resultant error in retrieved surface and atmospheric temperatures, due to use of an incorrect surface emissivity in inverting infra-red radiance observations, are discussed and found to be significant.

In many applications of the radiative transfer equations to obtain estimates of surface temperatures and atmospheric temperature profiles it is common to find the surface emissivity assumed to be unity. Observations (Kondratyev, 1965, Buettner and Kern 1965, Hovis 1966) show that the land's surface emissivity may differ appreciably from unity. Shaw (1970) discussed the effect of non-unit surface emissivity on surface temperature measurements in the 3.7 μm region. Our purpose is to emphasize the importance of considering both atmospheric transmission and surface emissivity in the design of atmospheric temperature profile sounders used over land surfaces. We do this by providing estimates of possible errors introduced by assuming unit emissivity with present day atmospheric temperature sounders.

Satellite temperature retrievals are usually based on inversions of the spectral radiative transfer equations. These equations in the absence of clouds and scattering may be written simply for a multichannel sensor as:

$$R_i = [\epsilon_i B_i(T_s) + (1 - \epsilon_i) \hat{R}_i \downarrow] \tau_{si} + \int_{\tau_{si}}^{1} B_i \, d\tau_i \tag{1}$$

where R_i is the spectral radiance observed by the satellite in channel i, $\hat{R}_i \downarrow$ is an effective downward flux, ϵ_i is the surface spectral emissivity, assumed to be isotropic, B_i is Planck's spectral radiance function evaluated at a characteristic frequency ν_i for each channel, T_s is the surface temperature, $\tau_i(P)$ is the spectral transmittance, averaged over sounding channel i, from the top of the atmosphere to pressure P, τ_{si} is $\tau_i(P_s)$, and P_s is the surface pressure.

A first order estimate of the bias introduced by an incorrect value of the surface emissivity in a window channel can be obtained from (1) by assuming perfect transmission (neglecting radiation emitted and absorbed by the atmosphere). In this case, (1) reduces to

$$R_i = \epsilon_i \, B_i(T_s) = \frac{\epsilon_i \, A_i}{e^{b_i/T_s} - 1} \qquad (2)$$

where $b_i = 1.439\ \nu_i$, $A_i = 11.91 \times 10^{-6}\ \nu_i^3$, and ν_i is in cm^{-1}. Given an observation R_i, T can be calculated, assuming ϵ_i is known, according to

$$T = \frac{b_i}{\ln\left(1 + \frac{\epsilon_i \, A_i}{R_i}\right)} \quad . \qquad (3)$$

Use of an incorrect emissivity, ϵ_i', in (3) will have produced an incorrect temperature, T', given by

$$T' = \frac{b_i}{\ln\left(1 + \frac{\epsilon_i' \, A_i}{R_i}\right)} \qquad (4)$$

with an error, T-T', given by

$$\Delta T = b_i \left[\frac{1}{\ell n \left(1 + \frac{\epsilon_i A_i}{R_i} \right)} - \frac{1}{\ell n \left(1 + \frac{\epsilon_i' A_i}{R_i} \right)} \right] \tag{5a}$$

$$= \frac{TT'}{b_i} \ell n \left[\frac{\left(1 + \frac{\epsilon_i' A_i}{R_i} \right)}{\left(1 + \frac{\epsilon_i A_i}{R_i} \right)} \right] . \tag{5b}$$

The expression in (5b) can be well approximated by the simple form

$$\Delta T \approx \frac{T_s^2}{b_i} \ell n \left(\frac{\epsilon_i'}{\epsilon_i} \right) = \frac{T_s^2 \ \ell n (\epsilon_i' / \epsilon_i)}{1.439 \ \nu_i} \tag{6}$$

because T' differs from T by at most a few percent (for a reasonable ϵ_i') and $\frac{\epsilon A_i}{R_i}$ and $\frac{\epsilon' A_i}{R_i}$ are large compared to 1.

The bias error for the $3.7\mu m$ and $11\mu m$ window channels of the HIRS instrument may be estimated by using (6). In the $3.7\mu m$ region of the spectrum emissivities have been observed which range from .6 and .9 over land. At a surface temperature of 290 K, if the true emissivity was .6 and an assumed emissivity of .8 is used to estimate the surface temperature, an error of 6°C would result. If a unit emissivity is assumed the error would be approximately 11°C.

In the 11 μm region of the spectrum emissivities which differ from unity by as much as .05 have been observed. At a surface temperature of 290°K (if the true emissivity is .95) a bias error of 3.5 K results if a unit emissivity is assumed; if the emissivity is assumed to be .97 an error of 1.4 K would result.

The effects of non-unit surface emissivity on temperature retrievals from multichannel atmospheric temperature sounders such as VTPR and HIRS are smaller than in the case of window channel surface temperature sounders because the atmospheric transmittance τ_{si} is considerably less than 1, even for the channel sounding deepest in the atmosphere, and because the effective downward flux, $\hat{R}_i \downarrow$, tends to augment some of the decreased radiation coming from the surface. Note for example, that if $\hat{R}_i \downarrow = B_i(T_s)$, (1) becomes equivalent to the case of unit emissivity. Before this effect can be assessed, one must first be able to evaluate or model $\hat{R}_i \downarrow$.

The actual expression for the term involving $\hat{R}_i \downarrow$ is given by

$$(1-\epsilon_i)\hat{R}_i \downarrow \tau_{si} = \int_0^\infty \tau_{s\nu} f_i(\nu) \{\int_0^{2\pi} \int_0^{\pi/2} [1-\epsilon_{\nu,d}(\theta,\varphi)] R_\nu \downarrow (\theta) \cos\theta \sin\theta \, d\theta \, d\varphi\} d\nu . \tag{7}$$

In the above, $\tau_{s\nu}$ is the monochromatic atmospheric transmittance to the surface, $f_i(\nu)$ is the instrumental filter function for channel i, $\epsilon_{\nu,d}$ is the directional surface emissivity in the upward direction, and $R_\nu \downarrow (\theta)$ is the monochromatic downward flux striking the earth's surface at zenith angle θ, given by (neglecting solar radiation)

$$R_\nu \downarrow (\theta) = \int_{\tau_{s\nu}(\theta)}^{1} B_\nu(\tau') \, d\tau' \tag{8}$$

where $\tau'_\nu(\theta,P)$ represents the monochromatic transmittance from pressure P to the surface and $B_\nu(\tau')$ is a shortened notation for $B_\nu[T(\tau')]$. All functions are assumed to be isotropic in azimuth angle φ.

To the extent that the surface is Lambertian and $R_\nu \downarrow (\theta)$ is isotropic (actually, $R_\nu \downarrow (\theta)$ increases somewhat with θ) (7) becomes

$$(1-\epsilon_i) \hat{R}_i \downarrow \tau_{si} = \int_0^\infty \tau_{s\nu} f_i(\nu) (1-\epsilon_\nu) R_\nu \downarrow d\nu \tag{9}$$

where $\pi(1-\epsilon_{\nu,d}(\theta,\varphi))$ has been replaced by the monochromatic reflectivity, $(1-\epsilon_\nu)$ (Shaw, 1970).

The right hand side of (9) involves the average of the product of three frequency dependent quantities and cannot be replaced by the product of the averages. The emissivity can be factored out of (9) because it is roughly constant across the bandpass of the filter function $f_i(\nu)$, with a value ϵ_i. The effective channel averaged downward flux can then be defined so as to identically obey (9) according to

$$\hat{R}_i \downarrow \equiv \frac{\int_0^\infty R_\nu \downarrow \ \tau_{s\nu} \ f_i(\nu)\, d\nu}{\int_0^\infty \tau_{s\nu} \ f_i(\nu)\, d\nu} = \frac{\langle R \downarrow \ \tau \rangle_{si}}{\tau_{si}} \quad . \tag{10}$$

The effective downward flux, $\hat{R}_i \downarrow$, is always less than the average downward flux $R_i \downarrow$, because, as seen from (8), $\tau_{s\nu}$ and $R_\nu \downarrow$ are negatively correlated.

The effective downward flux, as defined in (10), can be effectively modeled according to the form (developed in the Appendix)

$$\hat{R}_i \downarrow = F_i' \ B_i(T_s)\,(1 - \tau_{si}) \tag{11}$$

where F_i' is a constant depending only on sounding channel.

An estimate of the bias introduced into retrieved temperature profiles through an incorrect surface emissivity can now be obtained for multichannel sensors in the following way. The upward radiance measured at the sensors are first calculated, using (1) and (11), for a particular temperature profile with a nonunit surface emissivity. These calculated radiances are then used to obtain a retrieved temperature profile with an assumption of unit emissivity. The difference between the original and retrieved temperature profiles serves as a measure of the bias. This approach has been applied to the multichannel VTPR instrument using the U.S. standard atmosphere temperature profile (1966), applying Chahine's method for temperature retrieval (Chahine, 1968). The surface (1000 mb) relative humidity of the standard atmosphere was assumed to be 70%. The absolute humidity decreased exponentially with a scale height of 2.1 km. The atmospheric transmittances, $\tau(P)$, were obtained for each VTPR channel through line-by-line calculations. Nadir viewing was assumed in the calculations. The effective downward flux term was calculated according to (11) with F_i' set equal to .53 and .68 for the two lowest temperature sounding channels and 1 for the remaining channels.

Observed radiances were computed for surface emissivities of .95, and .98. Using the standard profile as an initial guess and an assumed unit emissivity, retrieved profiles were obtained for each case.

The retrieved profile for the .95 emissivity was in error by 1.8° at the surface and produced a .65°C RMS error at the 10 lowest mandatory levels. The bias in calculated clear column radiances caused by assuming an incorrect unit emissivity was on the order of 1% in the surface channel, a value four times greater than the instrumental noise level of the channel (Fritz et al., 1972). The retrieved profile for the .98 emissivity was in error by .48°C at the surface and produced a .17°C RMS at the same mandatory levels. The bias in the clear column radiance for the surface channel was approximately twice the nominal noise level. The temperature bias is greatest at the surface and decreases with altitude. Greatest errors occur for colder temperature profiles because of increased atmospheric transmission.

The procedure was repeated for the HIRS instrument. In this case only the 4.3 μm channels were used to retrieve lower tropospheric temperatures (Chahine, 1974). F_i' was set equal to .42 and .55 for the two lowest temperature sounding channels. Observed radiances were computed for surface emissivities of .85 and .95 typical of land and water in this spectral region. Retrievials were done as above with assumed unit emissivity for each case.

The retrieved profile for .85 emissivity was in error by 3.1° at the surface and produced a 1.34°C RMS error at the 10 lowest mandatory levels. The calculated clear column radiance for the surface channel was in error by 9% in the surface channel when unit emissivity was assumed. The retrieved profile for the .95 emissivity was in error by 1.0°C at the surface with an RMS error of .43°C. The calculated clear column radiance for the surface channel was in error by 3%.

The temperature bias estimates indicate incorrect surface emissivities may produce sizeable bias in the surface temperatures and temperature profiles retrieved by satellites over land, and point to the necessity of providing for surface emissivities in future sounder design.

APPENDIX

Model of Downward Flux

The effective downward flux for a particular temperature profile is defined in (10) in the main text. Given a temperature profile, all terms on the right hand side of (10) can be calculated using line by line calculations. This procedure is very time consuming however, and it is much more convenient to use an empirical model which gives close agreement with exact calculation in a number of cases. The form of the model comes from examination of (8) in the text which can be rewritten as

$$R_\nu \downarrow = \int_{\tau_\nu(P_s)}^{1} B_\nu(\tau')\, d\tau' = \int_{\tau_\nu(P_s)}^{1} B_\nu(T_s)\, d\tau' + \int_{\tau_\nu(P_s)}^{1} [B(\tau') - B(T_s)]\, d\tau'$$

$$= B_\nu(T_s)(1 - \tau_\nu(P_s)) + \int_{\tau_\nu(P_s)}^{1} [B_\nu(\tau') - B_\nu(T_s)]d\tau' \quad . \tag{1}$$

Most of the absorption takes place very low in the atmosphere, say the lowest 150 mb (i.e., between 1000 and 850 mb). $B(\tau) - B(T_s)$ is a slowly varying function over this region, and (1) can be well approximated by the mean value theorem to give

$$R_\nu \downarrow \approx B_\nu(T_s)(1-\tau_\nu(P_s)) + \overline{B_\nu - B_\nu(T_s)} \quad (1 - \tau_\nu(P_s)) \tag{2}$$

where $\overline{B - B(T_s)}$ is a mean difference between the atmospheric Planck function and the surface Planck function over the range of most absorption. (2) can be rewritten in the form

$$R_\nu \downarrow = F_\nu B(T_s) (1 - \tau_\nu(P_s)) \tag{3}$$

where

$$F_\nu = 1 + \frac{\overline{B_\nu - B_\nu(T_s)}}{B_\nu(T_s)} \tag{4}$$

F_ν differs from "1" to the extent that the mean value of the Planck function differs from the surface Planck function. F_ν can be calculated for a particular profile in an exact manner by using (3) in the form

$$F_\nu = \frac{R_\nu \downarrow}{B_\nu(T_s)[1 - \tau_\nu(P_s)]} \tag{5}$$

with all of the values on the right-hand side of (5) calculated exactly in a line-by-line fashion.

Likewise, analogous channel averaged quantities are defined for a particular profile according to

$$F_i \equiv \int R_\nu \downarrow f_i(\nu)\, d\nu / B_i(T_s)(1 - \tau_{si}) = \frac{R_i \downarrow}{B_i(T_s)(1 - \tau_{si})} \tag{6}$$

and

$$F'_i \equiv \frac{\hat{R}_i\downarrow}{B_i(T_s)(1-\tau_{si})} = \frac{F_i\,\langle R\downarrow\tau\rangle_{si}}{R_i\downarrow\tau_{si}} \;. \tag{7}$$

F'_i, like F_i, can be calculated exactly for a number of profiles using a line-by-line approach. The results of three profiles for channels 6 and 7, the only VTPR channels for which the surface term is significant, and channels 14 and 15, the lower tropospheric HIRS $4.3\mu m$ channels are shown in Table 1. The surface pressure was taken to be 1000 mb. We observe that to a very good approximation, F'_i and F_i are fairly constant over the wide range of profiles. This indicates that the effective downward flux can be well approximated by

$$\hat{R}_i\downarrow \approx F'_i\;B_i(T_s)\;(1-\tau_{si}) \tag{8}$$

using mean values of .53 for F'_7 and .68 for F'_6 for VTPR and .42 for F'_{14} and .55 for F'_{15} for HIRS. The effective downward flux is overestimated by about 60% if the correlation effects between $R_\nu\downarrow$ and $\tau_\nu(P_s)$ are not explicitly taken into account and F_i used in place of F'_i in (8).

TABLE 1

F_i, F'_i for downward flux calculations

(radiance in mw/met^2 - ster - cm^{-1})

	Temp. Profile	$\langle R\downarrow\tau\rangle_{si}$	τ_{si}	$R_i\downarrow\tau_{si}$	$R_i\downarrow/B_i(T_s)(1-\tau_{si}) = F_i$	$\frac{F_i\langle R\downarrow\tau\rangle_{si}}{R_i\downarrow\tau_{si}} = F'_i$
VTPR	July 0°N	10.23	.117	13.65	.927	.695
Channel 6	Apr. 40°N	9.77	.141	13.33	.923	.676
(725 cm^{-1})	Jan. 70°N	8.23	.189	11.54	.941	.671
VTPR	July 0°N	17.64	.372	29.19	.894	.540
Channel 7	Apr. 40°N	14.89	.421	25.12	.889	.527
(749 cm^{-1})	Jan. 70°N	10.20	.510	17.53	.911	.530
HIRS	July 0°N	.3283	.4068	.5309	.6755	.417
Channel 14	Apr. 40°N	.1925	.4287	.3130	.5706	.412
(2190 cm^{-1})	Jan. 70°N	.0673	.4684	.1088	.7398	.458
HIRS	July 0°N	.2142	.1552	.2938	.7389	.539
Channel 15	Apr. 40°N	.1278	.1612	.1768	.7408	.535
(2210 cm^{-1})	Jan. 70°N	.0456	.1700	.0625	.8184	.597

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